Simulation of the Stick-Slip Friction between Steering Shafts Using ADAMS/PRE

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ABSTRACT

Cyclic stick-slip friction is a well-known phenomenon in which the relative motion between two parts involved is intermittent. The relative motion due to external excitation, support compliance of the parts in contact, and the difference between the static and kinetic friction coefficients contribute to this cyclic stick-slip motion. This paper presents a study on how various vehicle parameters affect the stick-slip vibration in the slider joint between steering intermediate shafts. The vibration was simulated using a full vehicle ADAMS model for a maneuver where the vehicle is braking while negotiating a sharp corner. The steering subsystem, which was elaborated in ADAMS/PRE templates for this particular issue, consists of the steering wheel, the steering column, the pinion input shafts, the upper and lower intermediate shafts. The cornering and braking event generates the relative velocity and the torque between the intermediate shafts, which are the most important contributing factors leading to the cyclic friction. The simulation was able to duplicate the stick-slip vibration observed in road tests.

INTRODUCTION

Stick-slip friction has been widely studied in the engineering [1,3]. Since there are always many uncertainties affecting the friction mechanism, the control of the friction is still a challenging engineering problem, although it is well known that the nature of the friction is the negative slope of the friction force with respect to the relative sliding velocity. Experiments have been indispensable to understand the basic physics of the stick-slip friction. For larger mechanical systems, however, CAE modeling has to be used to analyze the effects of the stick-slip friction on the system behavior. Various friction models can be found in the literature [2,3,4]. Many of them have limitations in engineering applications due to discontinuity and availability of parameters. For the problem to be discussed in the following, the continuity of friction model as well as the availability of parameters must be taken into account for robust simulations and feasible parametric studies.

Cyclic stick-slip vibration in the steering shafts is the phenomenon in which the relative motion between the lower and upper intermediate shafts is intermittent. This phenomenon was observed in road tests when a vehicle was cornering sharply while braking. The axial acceleration at the steering wheel was sensible. During the brake, the body and frame pitch at the different rates, thus causing the small relative displacement between the upper and lower intermediate steering shafts, since the lower intermediate shaft is connected to the frame through the input shaft and the gear while the upper intermediate shaft is connected to the body through the steering column and the instrument panel.

The compliance between the body and the upper intermediate shaft as well as that between the frame and the lower intermediate shaft is physically not zero. From the discussion in [1], the values of the compliance and the relative velocity must form a region where the stick-slip motion could occur. In the extreme cases where the compliance is very small or the relative velocity is high enough, the stick-slip would disappear. However, due to steering system degradation or the manufacturing tolerances, the stick-slip region could be reached under the vehicle maneuver we are concerned with.

STICK-SLIP FRICTION MODEL

The core part of modeling the stick-slip induced steering vibration is the friction force abrupt decrease when the relative velocity changes from zero to a moderate value. The negative force-velocity gradient yields a impact on both parts involved. This impact depends on the difference between the static and kinetic friction coefficients as well as on the joint normal (transverse) force. The friction force is determined by the friction coefficient and the normal force as

$$\mathbf{F}_{ss} = \mu(\Delta V_s)\mathbf{N}_s(\mathbf{F}_{pre}, \mathbf{F}_{dyn}, \mathbf{T}_{sw}) \,,$$

where the normal force $\mathbf{N}_s$ is determined by the joint preload $\mathbf{F}_{pre}$, the dynamic load in the joint $\mathbf{F}_{dyn}$, and the steering wheel torque $\mathbf{T}_{sw}$ as such

$$\mathbf{N}_s = \left| \frac{\mathbf{M}_Z}{r} + \frac{2\sqrt{\mathbf{M}_X^2 + \mathbf{M}_Y^2}}{l} + \sqrt{\mathbf{F}_X^2 + \mathbf{F}_Y^2} \right|$$

The torque $\mathbf{M}_Z$ is directly related to the steering wheel torque $\mathbf{T}_{sw}$; the transverse loads in the joint $\mathbf{F}_X$ and $\mathbf{F}_Y$ are the X and Y components of the dynamic load $\mathbf{F}_{dyn}$ and the preload $\mathbf{F}_{pre}$. The shafts bending moments $\mathbf{M}_X$ and $\mathbf{M}_Y$ are also included in the calculation. In addition, two geometric parameters are required - the effective radius of the intermediate shafts r and the intermediate shaft overlap length l. The friction coefficient $\mu(\Delta V_s)$ is a function of the relative velocity ΔV_s, which is given in the following:

$$\mu(\Delta V_s) = \mu_0 \sin(C \arctan((B\Delta V_s) - E((B\Delta V_s) - \arctan(B\Delta V_s)))),$$

where the coefficients μ_0, B, C, and E are chosen to fit the measured friction curve. For the simulations reported in this paper, we chose B = 0.5 and E = -2.0. μ_0 is the static friction coefficient. The relative friction coefficient curves $[\mu(\Delta V_s)/\mu_0]$ with these values for C = 1.0, C = 1.2, C = 1.4, and C = 1.7 were depicted in Figure 1. The friction model is a smooth function which could closely approximate arbitrary friction characteristics without sacrificing the accuracy.

VEHICLE MODEL

A full vehicle model was built using ADAMS/PRE [5] modified templates to include the steering intermediate shaft friction and to correct the part connectivity for allowing the relative motion between the body and the frame. The model includes the body, the frame, the front and rear suspensions, as well as the steering system. The indispensable compliance is introduced into the model through the body mounts, the bushings between the steering column and the instrument panel, and the bushings between the lower intermediate shaft and the steering gear. Figure 2 illustrates the ADAMS full vehicle model and Figure 3 shows the factors leading to the stick-slip vibration which are included in the model.

RESULTS AND DISCUSSION

Using the full vehicle model with the stick-slip friction, a brake-in-turn event was simulated with four scenarios. The deceleration was 0.6g while the vehicle started with a lateral acceleration 0.23g on a corner with the radius being 20 meters. The vehicle parameters for the scenarios are given in Table 1. The friction force, the relative displacement, and the relative velocity across the slider joint between the intermediate shafts for the first scenario are shown in Figures 4-6. The axial acceleration of the upper intermediate shaft for the difference scenarios was plotted in Figures 7-10. It can be seen that the zigzag friction force and velocity across the slide joint undulate cyclically between stick and slip phases during a very short stroke of the relative displacement. The friction force causes the cyclic acceleration at the intermediate shafts, as shown in Figures 7-10, which also indicate how the compliance and the friction coefficient difference affect the stick-slip vibration. The following results were observed:

- The stick-slip vibration is caused by the axial impact friction force due to the difference between the static and kinetic friction coefficients. This difference is a dominant factor causing the stick-slip vibration.
- The friction force or the axial acceleration is proportional to the transverse load in the slider joint, which is mainly contributed by the steering wheel torque.
- The compliance does not affect acceleration and force magnitudes significantly. However, it affects the stick-slip occurrence frequency. Very low occurrence frequency implies that no stick-slip cycles would appear during the short stroke of the relative displacement of the upper and lower intermediate shafts.

Table 1 Vehicle Parameters for the Simulation Scenarios

	Scenarios			
	1	2	3	4
Static friction coefficient	0.2	0.2	0.2	0.2
Coefficient C	1.7	1.4	1.7	1.7
Stiffness between column and body [N/mm]	1.431E3	1.431E3	1E3	1.431E3
Stiffness between input shaft and rack housing [N/mm]	1E4	1E4	1E4	2E4

Since the turning radius and the brake deceleration were not measured during road tests, no efforts were made to correlate the measured and simulated results. Moreover, the simulations could not converge if the turning radius is smaller than 20 meters. In spite of these shortcomings, the simulation results did agree with the road test results qualitatively.

CONCLUSIONS

As having been discussed in the preceding sections, various factors affect the stick-slip vibration - its occurrence frequency and the acceleration amplitude. The simulations reported in this paper revealed the most important factors leading to the stick-slip phenomenon which could appear in the steering intermediate shafts. The extended modeling capability and simulation results can assist in better understanding of the vibration for controlling the contributing factors. The developed simulation procedure can be readily used for various vehicle programs to examine the potential possibility of the stick-slip vibration if the compliance, as well as its variation can be measured or estimated. From our simulations presented in this paper, the following generic measures are recommended to suppress the stick-slip vibration:

- reducing the difference between the static and kinetic friction coefficients;
- controlling the axial lash or compliance in the steering column and shafts.

Perhaps it is more practical to minimize the impact force magnitude than to eliminate the stick-slip phenomenon completely. A lab test rig has been established based on the preliminary modeling work. Further efforts will be made to correlate the simulations with the controlled lab tests.

ACKNOWLEDGMENTS

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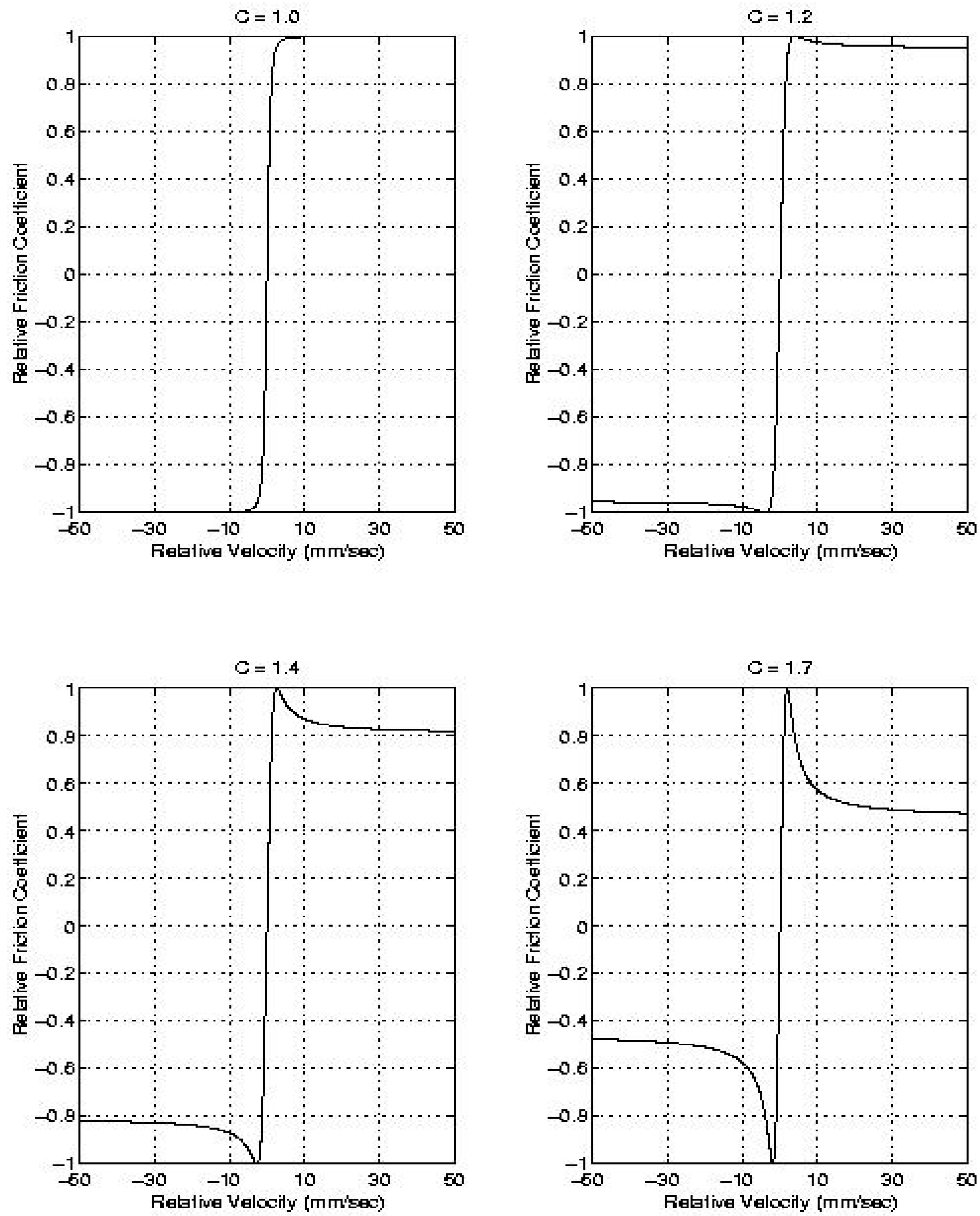

Figure 1. Relative Friction Coefficient Curves

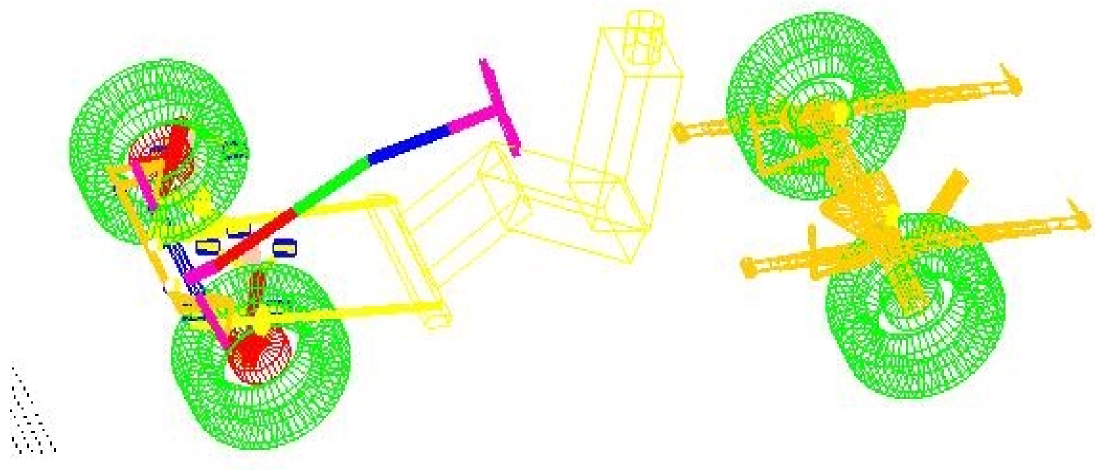

Figure 2. Illustration of the ADAMS Full Vehicle Model

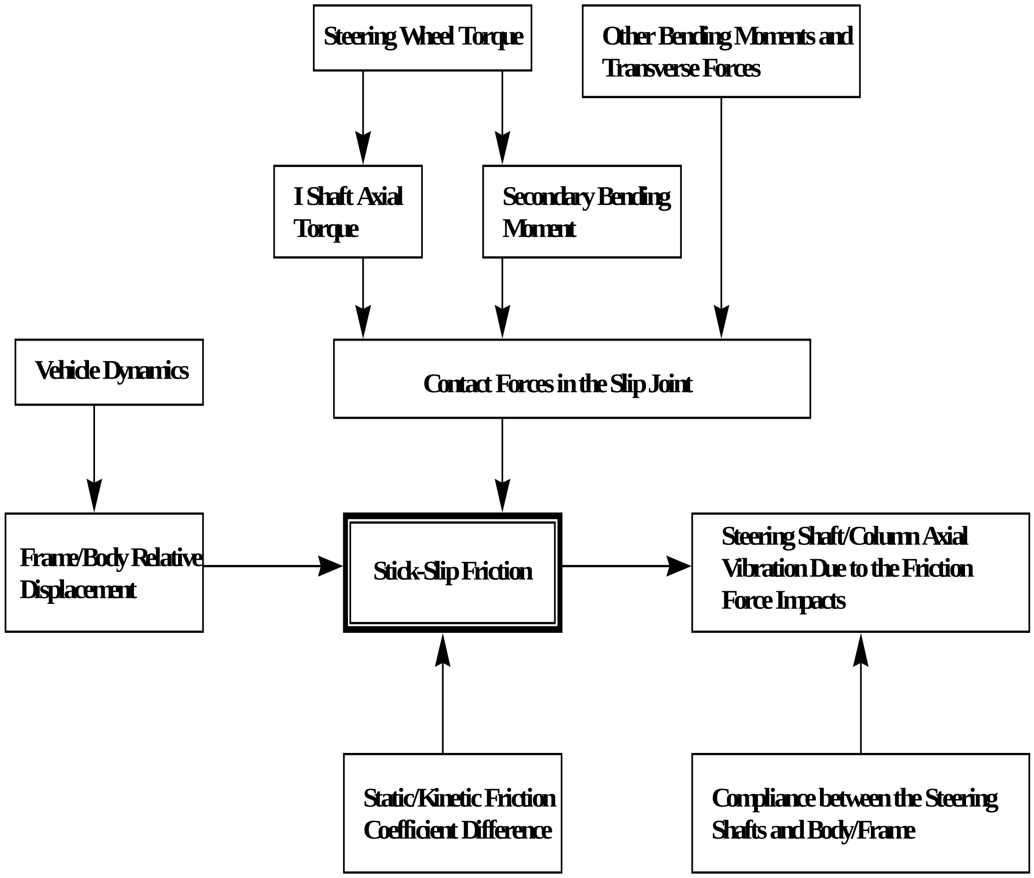

Figure 3. Factors Leading to the Stick-Slip Vibration in the Steering Shafts

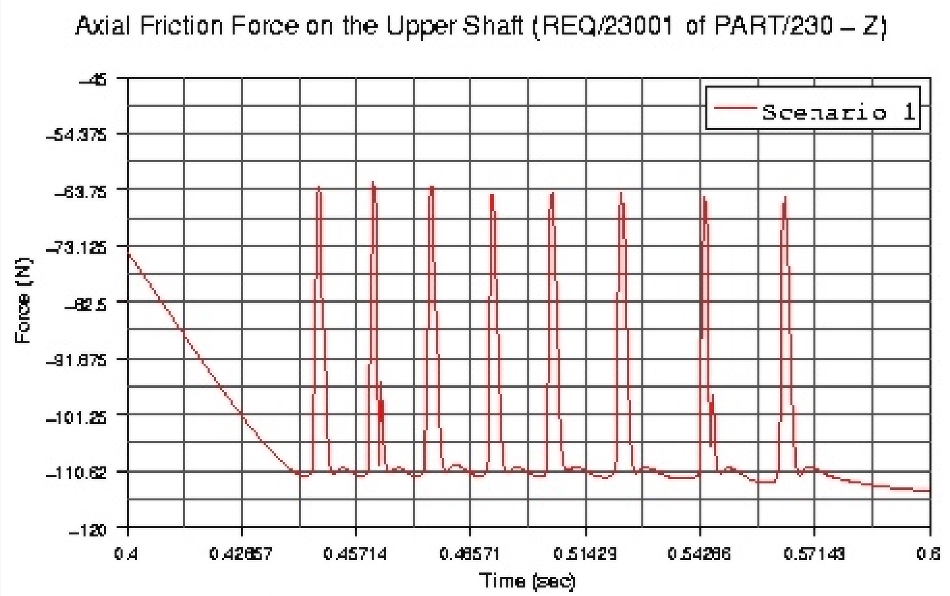

Figure 4. Axial Friction Force on the Upper Shaft

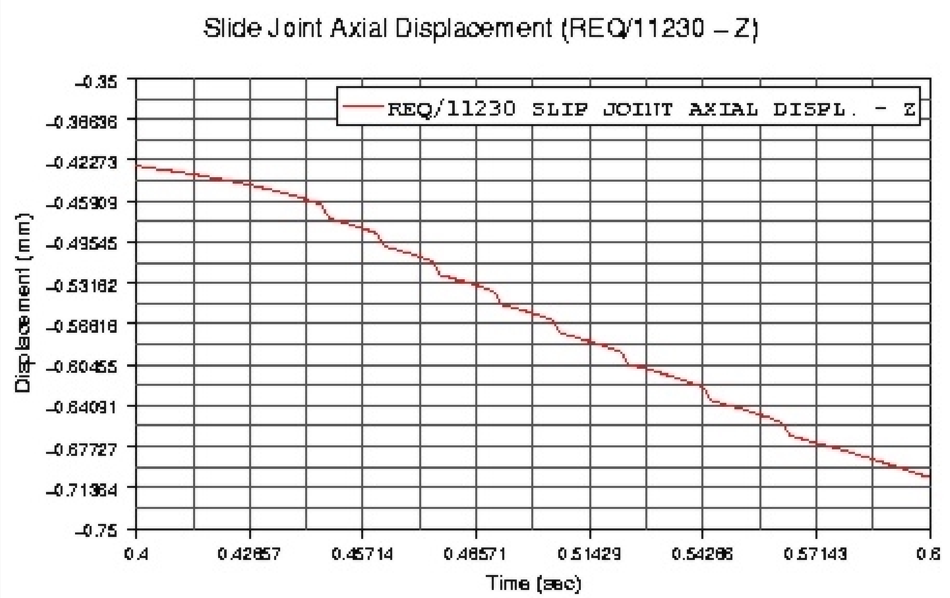

Figure 5. Slide Joint Axial Displacement

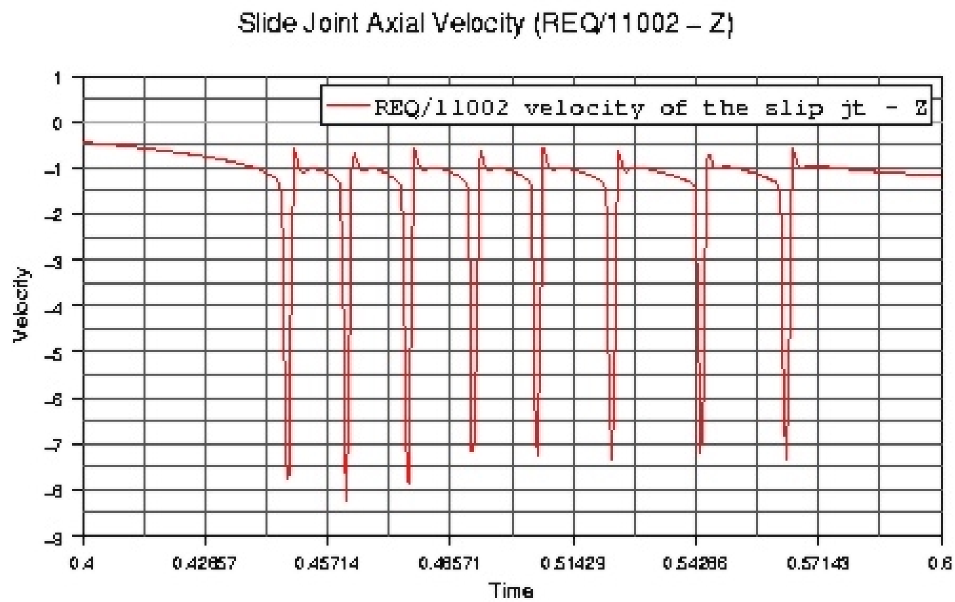

Figure 6. Slide Joint Axial Velocity

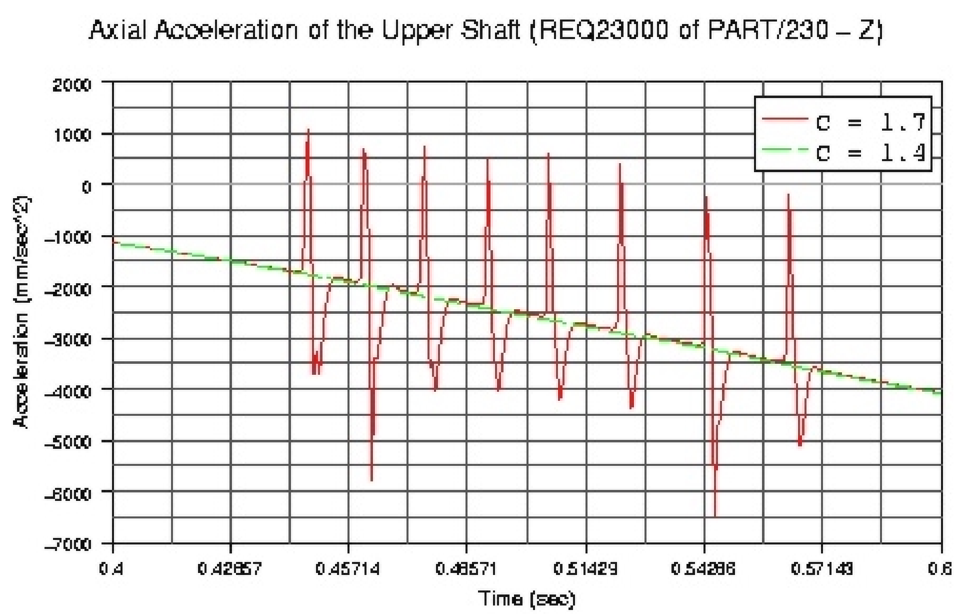

Figure 7. Axial Acceleration of the Upper Shaft (Friction Difference)

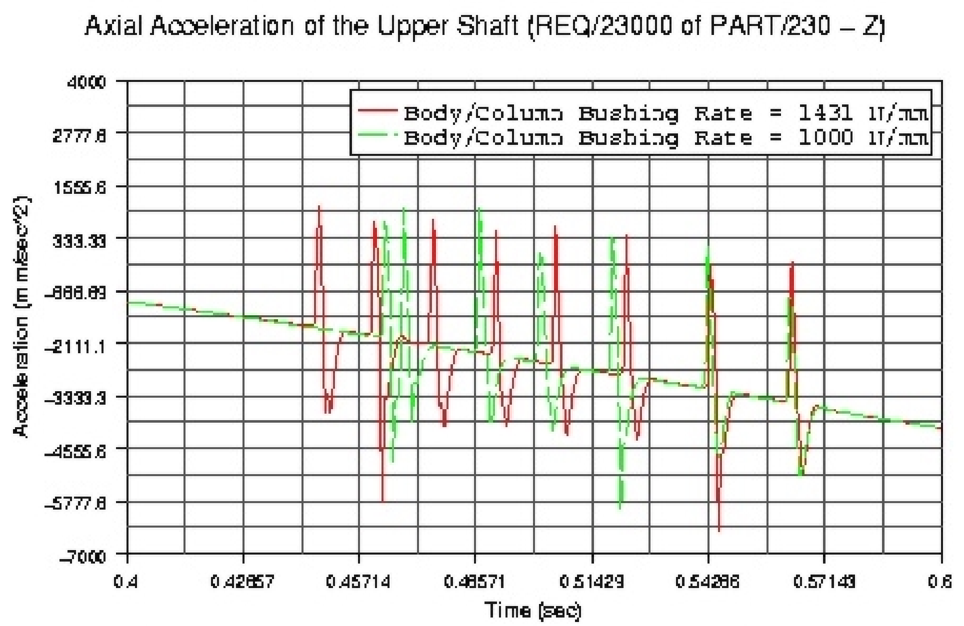

Figure 9. Axial Acceleration of the Upper Shaft (Upper Support Stiffness)

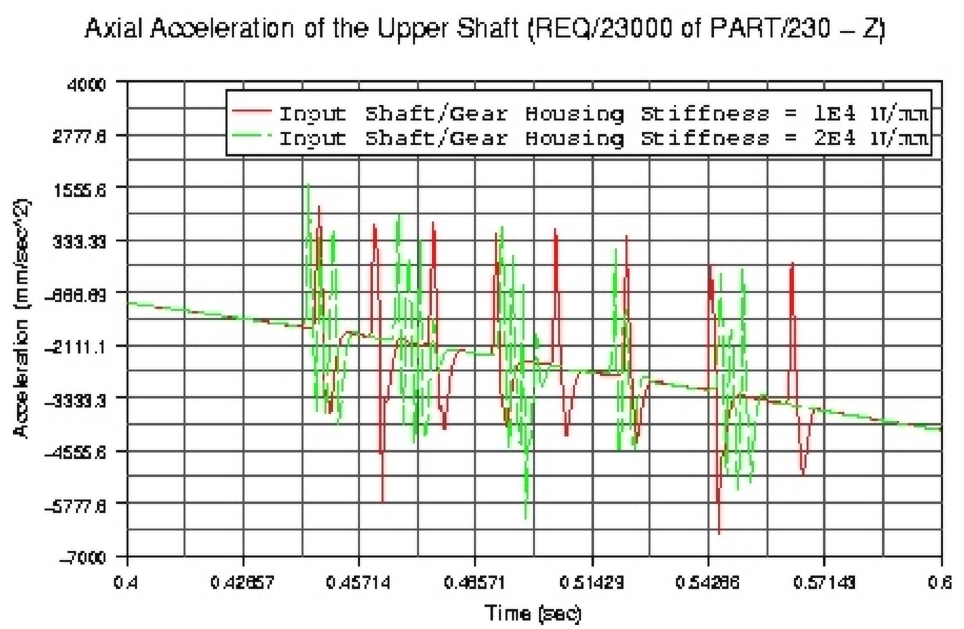

Figure 10. Axial Acceleration of the Upper Shaft (Lower Support Stiffness)